

# Exceeding the MSSM Higgs Mass Bound in a Special Class of U(1) Gauge Models

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## Abstract

A special class of supersymmetric U(1) gauge extensions of the standard model was proposed in 2002. It is anomaly-free, has no  $\mu$  term, and conserves baryon and lepton numbers automatically. It also allows the lightest Higgs boson to have a mass exceeding the MSSM (Minimal Supersymmetric Standard Model) bound, i.e. about 130 GeV, which is of current topical interest from LHC (Large Hadron Collider) data. This and other new aspects of this 2002 proposal are discussed.

Supersymmetry is a very attractive theoretical idea, but as the standard model of particle interactions is extended to include supersymmetry, several new problems arise.

- (1) Whereas the particle content of the  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge group of the standard model (SM) guarantees automatically the conservation of both baryon number  $B$  and lepton number  $L$ , as far as renormalizable interactions are concerned, the superfield content of its supersymmetric extension allows trilinear terms in its superpotential which violate both  $B$  and  $L$ . As a result, the proton would decay immediately, rendering impossible our existence. Even with the conventional imposition of  $R$  parity, i.e.  $R \equiv (-1)^{2j+3B+L}$ , which forbids these terms, effective dimension-five operators still exist in supersymmetry which mediate proton decay, whereas in the standard model, such operators are dimension-six.
- (2) The  $\mu\hat{\phi}_1\hat{\phi}_2$  term in the superpotential of the two Higgs superfields  $\hat{\phi}_{1,2}$  is invariant under supersymmetry, hence there is no understanding as to why the value of  $\mu$  is also close to (and not much higher than) the presumed scale of supersymmetry breaking, i.e. 1 TeV or so, which is required for supersymmetry to be relevant in solving the hierarchy problem of the standard model and the rationale for adopting it in the first place.
- (3) Supersymmetry imposes an upper bound on the mass of the lightest physical Higgs scalar boson  $H_1^0$  of about 130 GeV [1], which is reached in the limit of large  $\tan\beta = v_2/v_1 = \langle\phi_2^0\rangle/\langle\phi_1^0\rangle$ . In the decoupling limit,  $H_1^0 = \phi_1^0\cos\beta + \phi_2^0\sin\beta$  is essentially identical to the one physical Higgs boson  $H^0$  of the standard model. The current experimental lower bound [2] on the mass of  $H^0$  is 114.4 GeV from LEP2, with the exclusion of 158 to 175 GeV from the Tevatron. However, recent LHC data [3] have excluded most of the mass region above 150 GeV to 450 GeV. If there is no Higgs

boson below 130 GeV, the MSSM (Minimal Supersymmetric Standard Model) would be excluded, unless the supersymmetry breaking scale is much greater than 1 TeV.

In 2002, a remarkable class of supersymmetric  $U(1)_X$  anomaly-free gauge extensions of the standard model was discovered [4], with particle content given in Table 1. It addresses all three of the above issues.

superfield	copies	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_X - (A)$	$U(1)_X - (B)$
$\hat{Q} = (\hat{u}, \hat{d})$	3	$(3, 2, 1/6)$	$n_1$	$n_1$
$\hat{u}^c$	3	$(3^*, 1, -2/3)$	$(7n_1 + 3n_4)/2$	$5n_1$
$\hat{d}^c$	3	$(3^*, 1, 1/3)$	$(7n_1 + 3n_4)/2$	$2n_1 + 3n_4$
$\hat{L} = (\hat{\nu}, \hat{e})$	3	$(1, 2, -1/2)$	$n_4$	$n_4$
$\hat{e}^c$	3	$(1, 1, 1)$	$(9n_1 + n_4)/2$	$3n_1 + 2n_4$
$\hat{N}^c$	3	$(1, 1, 0)$	$(9n_1 + n_4)/2$	$6n_1 - n_4$
$\hat{\phi}_1 = (\hat{\phi}_1^0, \hat{\phi}_1^-)$	1	$(1, 2, -1/2)$	$-(9n_1 + 3n_4)/2$	$-3n_1 - 3n_4$
$\hat{\phi}_2 = (\hat{\phi}_2^+, \hat{\phi}_2^0)$	1	$(1, 2, 1/2)$	$-(9n_1 + 3n_4)/2$	$-6n_1$
$\hat{S}_3$	2	$(1, 1, 0)$	$9n_1 + 3n_4$	$9n_1 + 3n_4$
$\hat{U}$	2	$(3, 1, 2/3)$	$-4n_1 - 2n_4$	$-6n_1$
$\hat{D}$	1	$(3, 1, -1/3)$	$-4n_1 - 2n_4$	$-6n_1$
$\hat{U}^c$	2	$(3^*, 1, -2/3)$	$-5n_1 - n_4$	$-3n_1 - 3n_4$
$\hat{D}^c$	1	$(3^*, 1, 1/3)$	$-5n_1 - n_4$	$-3n_1 - 3n_4$
$\hat{S}_2$	3	$(1, 1, 0)$	$-6n_1 - 2n_4$	$-6n_1 - 2n_4$
$\hat{S}_1$	3	$(1, 1, 0)$	$-3n_1 - n_4$	$-3n_1 - n_4$

Table 1:  $U(1)_X$  charges for all the superfields of this anomaly-free supersymmetric model. There are two possible solutions: (A) and (B).

- (1) As in the standard model, both  $B$  and  $L$  are separately conserved automatically, as far as renormalizable interactions are concerned, and there are no dimension-five operators which mediate proton decay [5]. Dimension-six operators exist if  $S_1$  has a vacuum expectation value.

- (2) The  $\mu\hat{\phi}_1\hat{\phi}_2$  term is replaced by  $f\hat{S}_3\hat{\phi}_1\hat{\phi}_2$ , where the singlet superfield  $\hat{S}_3$  transforms nontrivially under  $U(1)_X$ . The soft breaking of supersymmetry also breaks  $U(1)_X$ , so that the two scales are naturally the same. Note that in many supersymmetric gauge  $U(1)$  extensions of the standard model, such as those from  $E_6$ , which also eliminate the  $\mu$  term,  $B$  and  $L$  are in general not conserved, without the imposition of extra symmetries as in the MSSM. Here  $U(1)_X$  by itself is sufficient for this purpose. Note also that  $U(1)_{B-L}$  cannot eliminate the  $\mu$  term.
- (3) The MSSM bound of 130 GeV on the mass of  $H_1^0$  is allowed to be exceeded, because the Higgs sector now includes a singlet [6]. For a specific  $U(1)$  gauge factor, there is still a bound, which has been discussed over the years [7, 8, 9, 10, 11, 12]. However, for most known supersymmetric  $U(1)$  models [13, 14], 144 GeV is still difficult to reach. (This value of 144 GeV is chosen for illustration. It can be replaced by any value above 135 GeV or so.) In this special class of  $U(1)_X$  models, it will be shown that the  $H_1^0$  mass is allowed to be 144 GeV, while keeping the supersymmetry breaking scale at 1 TeV. It also has verifiable predictions at the LHC in terms of exotic new quarks.

In the above, all superfields are left-handed, with the usual right-handed fields represented by their charge conjugates. There are three copies each of  $\hat{Q}, \hat{u}^c, \hat{d}^c, \hat{L}, \hat{e}^c, \hat{N}^c, \hat{S}_2, \hat{S}_1$ , two copies each of  $\hat{U}, \hat{U}^c, \hat{S}_3$ , and one copy each of  $\hat{\phi}_1, \hat{\phi}_2, \hat{D}, \hat{D}^c$ . The resulting field theory is free of all three possible quantum anomalies, i.e. axial-vector, global  $SU(2)$ , and mixed gravitational-gauge, for all values of  $n_1$  and  $n_4$  in both solutions (A) and (B) [4]. The allowed interactions in all cases are

$$\hat{Q}\hat{u}^c\hat{\phi}_2, \quad \hat{Q}\hat{d}^c\hat{\phi}_1, \quad \hat{L}\hat{e}^c\hat{\phi}_1, \quad \hat{L}\hat{N}^c\hat{\phi}_2, \quad \hat{S}_3\hat{\phi}_1\hat{\phi}_2, \quad \hat{S}_3\hat{U}\hat{U}^c, \quad \hat{S}_3\hat{D}\hat{D}^c, \quad \hat{S}_3\hat{S}_1\hat{S}_2. \quad (1)$$

The  $U(1)_X$  gauge symmetry is broken by  $\langle S_3 \rangle$  for  $3n_1 + n_4 \neq 0$ , through which the particles contained in  $\hat{U}, \hat{U}^c, \hat{D}, \hat{D}^c, \hat{S}_{1,2,3}$  obtain their large masses. At the same time, an effective

$\mu\hat{\phi}_1\hat{\phi}_2$  term is generated.

Phenomenologically, the exotic new quarks must decay. Assuming that  $u^c$  is distinguished from  $U^c$  and  $d^c$  from  $D^c$  by  $U(1)_X$  (otherwise the  $3 \times 3$  quark mixing matrix would not be unitary), this requirement leads to two possible models if only renormalizable interactions are considered. A third possible model is shown as an example if higher-dimensional operators are included. There may be other viable examples of this kind.

- (1) As already discussed in Ref. [15],  $n_1 = 0$  in Solution (A) implies the following additional interactions:

$$\hat{u}^c \hat{e}^c \hat{D}, \quad \hat{u}^c \hat{N}^c \hat{U}, \quad \hat{d}^c \hat{N}^c \hat{D}, \quad \hat{Q} \hat{L} \hat{D}^c, \quad \hat{N}^c \hat{N}^c \hat{S}_1. \quad (2)$$

This means that scalar  $U, D$  are leptoquarks and their observation at the LHC is assured if kinematically allowed. The  $\hat{N}^c \hat{N}^c \hat{S}_1$  term also means that lepton number  $L$  becomes multiplicative, i.e.  $(-1)^L$ , and the neutrinos obtain small Majorana masses from the seesaw mechanism as  $\langle S_{1,2} \rangle$  also acquire vacuum expectation values.

- (2)  $n_4 = -n_1$  in Solution (B) implies the following additional interactions:

$$\hat{Q} \hat{L} \hat{D}^c, \quad \hat{u}^c \hat{e}^c \hat{D}, \quad \hat{d}^c \hat{N}^c \hat{D}, \quad \hat{U}^c \hat{D}^c \hat{D}^c. \quad (3)$$

This means that scalar  $D$  is a leptoquark and scalar  $U^c$  is a dileptoquark. However,  $\hat{D}^c \hat{D}^c$  in the term  $\hat{U}^c \hat{D}^c \hat{D}^c$  must transform as  $\underline{3}$  under  $SU(3)_C$ , i.e. antisymmetric, which is impossible for one copy of  $\hat{D}^c$ . To allow this term, a second pair of  $\hat{D}$  and  $\hat{D}^c$  should be added, with the new  $\hat{D}^c$  transforming as the existing  $\hat{D}^c$ , i.e. trivially under  $U(1)_X$ , and the new  $\hat{D}$  also trivially, i.e. differently from the existing  $\hat{D}$ , so that no new anomaly is generated. Neutrino masses come only from  $\langle \phi_2^0 \rangle$ , hence they are Dirac.

- (3)  $n_4 = n_1$  leads to the same model in both Solutions (A) and (B). However, no additional renormalizable interaction is implied. As such, the exotic quarks appear to be stable. Nevertheless, the higher-dimensional operators

$$\hat{d}^c \hat{d}^c \hat{U}^c \hat{S}_1, \quad \hat{d}^c \hat{u}^c \hat{D}^c \hat{S}_1, \quad \hat{u}^c \hat{N}^c \hat{U} \hat{S}_1, \quad \hat{d}^c \hat{N}^c \hat{D} \hat{S}_1, \quad (4)$$

are allowed, but suppressed by a large mass scale, such as the grand-unification scale of perhaps  $10^{16}$  GeV or the Planck scale of  $10^{19}$  GeV. The exotic quarks  $U$  and  $D$  now have  $B - L = -2/3$  and would decay into quarks and leptons through a dimension-five operator if  $S_1$  has a vacuum expectation value as in (1). Here neutrino masses come only from  $\langle \phi_2^0 \rangle$ , i.e. Dirac as in (2).

As  $S_1$  picks up a nonzero vacuum expectation value at the TeV scale,  $B - L$  is still conserved, but not  $B$  and  $L$  separately. this means that proton decay via  $p \rightarrow \pi^+ \bar{\nu}$  is possible, but it comes from a dimension-six operator as in the SM, suppressed by two powers of the large mass scale implied by Eq.(4).

All of the above cases forbid the terms

$$\hat{L} \hat{e}^c \hat{L}, \quad \hat{Q} \hat{d}^c \hat{L}, \quad \hat{u}^c \hat{d}^c \hat{d}^c, \quad \hat{L} \hat{\phi}_2, \quad (5)$$

which are otherwise allowed in the MSSM without the imposition of  $R$  parity. Thus  $B$  and  $L$  are conserved by the renormalizable interactions of this theory. The lowest-order higher-dimensional operator for proton decay is  $\hat{Q} \hat{Q} \hat{Q} \hat{L} \hat{S}_1$ , which is dimension-six if  $S_1$  has a vacuum expectation value as in (1) and (3).

Let the  $U(1)_X$  gauge coupling  $g_X$  be normalized by defining the charge of  $S_3$ , i.e.  $9n_1 + 3n_4$ , to be unity. Consider then the production of  $X$  at the LHC and its decay branching fraction into  $\mu^- \mu^+$ . Compare these to the case of a hypothetical  $Z'$  of the same mass, but with couplings to quarks and leptons as in the standard model. Their relative factors are given in Table 2.

Model	Production	$B(\mu^-\mu^+)$	Event Ratio	$\text{Max}(g_X^2)$
SM	0.47	0.03	1	—
(1)	3/4	5/189	1.41 ( $g_X^2/g_Z^2$ )	0.394
(2)	3/2	2/261	0.82 ( $g_X^2/g_Z^2$ )	0.680
(3)	13/24	26/549	1.82 ( $g_X^2/g_Z^2$ )	0.305

Table 2: Relative factors of production and decay at the LHC for a standard-model  $Z'$  and the  $X$  boson in models (1),(2),(3). The maximum allowed value of  $g_X^2$  is obtained if  $m_X = 2$  TeV is assumed.

The production is assumed to be proportional to  $2[(g_L^u)^2 + (g_R^u)^2] + (g_L^d)^2 + (g_R^d)^2$ , and the decay branching fractions of  $Z'$  and  $X$  to  $\mu^-\mu^+$  assumes that their only decay products are the usual leptons and quarks, including  $t\bar{t}$  which is of course not possible for the actual  $Z$  boson at 91.2 GeV. The event ratio for observing  $\mu^-\mu^+$  relative to the standard model is in units of  $g_X^2/g_Z^2$ . From the nonobservation of a standard-model  $Z'$  below about 2 TeV at the LHC [16, 17], an upper bound on  $g_X^2$  is obtained if  $m_X = 2$  TeV is assumed. These bounds are relaxed if  $X$  decays into particles other than the usual leptons and quarks, or if  $m_X > 2$  TeV.

The effective two-Higgs-doublet potential of any supersymmetric  $U(1)_X$  gauge extension of the standard model is given by

$$\begin{aligned}
V = & m_1^2 \phi_1^\dagger \phi_1 + m_2^2 \phi_2^\dagger \phi_2 + m_{12}^2 (\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1) \\
& + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1),
\end{aligned} \tag{6}$$

where [13]

$$\lambda_1 = \frac{1}{4}(g_1^2 + g_2^2) + 2af^2 - \frac{f^4}{g_X^2}, \tag{7}$$

$$\lambda_2 = \frac{1}{4}(g_1^2 + g_2^2) + 2(1-a)f^2 - \frac{f^4}{g_X^2}, \tag{8}$$

$$\lambda_3 = -\frac{1}{4}g_1^2 + \frac{1}{4}g_2^2 + f^2 - \frac{f^4}{g_X^2}, \tag{9}$$

$$\lambda_4 = -\frac{1}{2}g_2^2 + f^2. \quad (10)$$

In the above, the contributions of the soft supersymmetry breaking scalar trilinear term  $fA_f S_3 \phi_1 \phi_2$  are assumed to be small, i.e.  $fA_f/g_X^2 \langle S_3 \rangle \ll 1$ . Also  $\phi_1$  in  $V$  has been redefined from  $(\phi_1^0, \phi_1^-)$  to  $(\phi_1^+, \phi_1^0)$  to agree with the usual convention for analyzing two Higgs doublets [18]. The  $U(1)_X$  charges of  $\phi_{1,2}$  in  $V$  are  $a$  and  $a-1$ . The upper bound on the  $H_1^0$  mass is then given by [13]

$$m^2(H_1^0) < M_Z^2 \cos^2 2\beta + \epsilon + f^2 v^2 [3 + 2(2a-1) \cos 2\beta - \cos^2 2\beta - 2f^2/g_X^2], \quad (11)$$

where  $v = 174$  GeV and [1]

$$\epsilon = \frac{3g_2^2 m_t^4}{8\pi^2 M_W^2} \ln \left( 1 + \frac{\tilde{m}_{eff}^2}{m_t^2} \right) \quad (12)$$

is the well-known radiative correction due to the  $t$  quark and its scalar counterparts which are represented by  $\tilde{m}_{eff}$ , usually set equal to 1 TeV. For a given value of  $g_X^2$ , this bound is maximized by

$$\frac{f^2}{g_X^2} = \frac{3}{4} + \left( a - \frac{1}{2} \right) \cos 2\beta - \frac{1}{4} \cos^2 2\beta, \quad (13)$$

resulting in

$$m^2(H_1^0) < M_Z^2 \cos^2 2\beta + \epsilon + \frac{1}{8} g_X^2 v^2 [3 + 2(2a-1) \cos 2\beta - \cos^2 2\beta]^2. \quad (14)$$

Now  $a = 1/2$  in both models (1) and (3). The bound on  $m^2(H_1^0)$  is maximized for  $\cos^2 2\beta = 1$ , i.e.

$$m^2(H_1^0) < M_Z^2 + \epsilon + \frac{1}{2} g_X^2 v^2, \quad (15)$$

which is consistent with  $m(H_1^0) = 144$  GeV if  $g_X^2 > 0.292$ . According to Table 2, this is allowed by both models. On the other hand, the  $Z-X$  mixing angle is given by [13]

$$\theta_{ZX} \simeq -\frac{g_Z g_X (\sin \beta - a) v^2}{m_X^2}, \quad (16)$$



which must be very small, say  $5 \times 10^{-4}$ . For  $\sin^2 \beta = 1$  and  $a = 1/2$ ,  $g_X^2 = 0.292$ ,  $m_X > 3.5$  TeV is required. This means that the bounds in Table 2 are relaxed for both models.

If  $\sin^2 \beta = 1/2$ , there is no  $Z - X$  mixing and  $m_X$  is not constrained. Now

$$m^2(H_1^0) < \epsilon + \frac{9}{8}g_X^2 v^2, \quad (17)$$

and  $m(H_1^0) = 144$  GeV requires  $g_X^2 > 0.374$  which is still possible in model (1).

For model (2),  $a = 0$ . Now

$$m^2(H_1^0) < M_Z^2 \cos^2 2\beta + \epsilon + \frac{1}{8}g_X^2 v^2 (1 - \cos 2\beta)^2 (3 + \cos 2\beta)^2. \quad (18)$$

If  $\tan \beta$  is large,

$$m^2(H_1^0) < \epsilon + 2g_X^2 v^2. \quad (19)$$

This is consistent with  $m(H_1^0) = 144$  GeV if  $g_X^2 > 0.073$ , which is allowed by Table 2. However,  $Z - X$  mixing requires  $m_X > 3.9$  TeV.

In summary, it has been shown that  $m(H_1^0) = 144$  GeV is possible in all three  $U(1)_X$  models (the first of which was considered earlier [15]), with different assumptions on the values of  $\cos 2\beta$  and  $m_X$  in each case. This would be especially important if experimental data rule out a Higgs boson below the MSSM bound of about 130 GeV. Each model is also associated with different predictions of how the exotic  $U$  and  $D$  quarks and scalar quarks decay. As more data accumulate at the LHC, these ideas will be tested, and be rejected or reinforced.

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